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Loop Transient Measurements in Cleveland, South Carolina

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Design of telephone station equipment requires knowledge of 60 Hz and lightning disturbances which can appear on the telephone loop. To obtain useful data on the subject, we have developed a computer-based monitoring system with capability to acquire transient waveforms on a single loop. The system was installed in Cleveland, South Carolina for the 1978 lightning season. During this season, we recorded and analyzed about 8000 disturbances produced by lightning, power induction, and power system transients. We found that the lightning environment was in most respects less severe than that previously recorded in Washington, Connecticut, but that several unexpected types of disturbances were encountered. The results of the analysis are useful to designers of protectors and station equipment.

I. INTRODUCTION

The design of telephone equipment must accommodate lightning and 60-Hz disturbances which may be present at the network-terminal interface. To characterize these disturbances more thoroughly, the Protection Engineering Group has engaged in a monitoring program from which results obtained at Washington, Connecticut, are reported elsewhere in this issue.[1] As described in that article, the telephone plant at Washington, Connecticut was aerial, the local power distribution was delta, and minimal exposure to power transmission systems existed. For the second phase of this program, a computer-based transient monitoring system (TMS) was developed and installed in Cleveland, South Carolina during 1978. In contrast to the Washington location, the cable plant at Cleveland was primarily buried, the local power distribution was multi-grounded neutral, and the cable route was exposed to several power transmission systems. It was desired to determine if different plant characteristics would produce major changes in the data obtained. The results from Cleveland are presented in this article and contrasted with previous measurements.

II. ROUTE AND SITE CHARACTERISTICS

The monitoring location was Cleveland, South Carolina, a rural community in hilly terrain about 30 miles northwest of Greenville. As in the Washington study, the equipment was located at the station end of a loop and monitored waveforms on that loop only. According to cable maps, the loop was 4.79 miles in length. It was terminated in the Cleveland step-by-step office by a main frame protector unit and 250-ohm resistors to ground which approximated the line relay impedance. No battery voltage was applied. The loop resistance was approximately 1000 ohms, exclusive of this termination. Service to the monitoring site was provided by 22 and 24 AWG metallic sheath PIC cable. Total bridged tap was 600 feet.

The loop was paralleled along most of its length by a 7.2 kV, three-phase, multigrounded-neutral power line mounted on poles. Earth resistivity ranged from 300 to 1000 meter-ohms at the monitoring structure, was 1000 to 2000 meter-ohms at the distribution terminal serving the structure, and varied from 400 to 11,000 meter-ohms along the route. Power system capacitor banks were located along the route at 1.0 and 2.1 miles from the central office, the latter of which exerted a significant influence on data obtained late in the study. Two aerial power transmission lines, 115 and 230 kV, crossed the loop 0.35 and 0.7 mile before the monitoring station. A power substation, fed by yet another line, was located approximately 1.0 mile beyond the monitoring station. Induced longitudinal voltage from the power lines, as measured by the true rms instrument built into the monitoring system, was typically 15-25 V rms, frequently exceeded 50 V rms for extended periods, and on 27 occasions briefly exceeded the system rms trigger which was set to 100 V rms.

The first half of the loop, which was H-88 loaded, contained aerial and buried segments while the last half was buried. An aerial drop of approximately 200 feet of Type F drop wire (four ohms per conductor) connected the station to the serving cable via a pedestal which contained 6-mil carbon blocks. The monitoring system was housed in a 12 $\times$ 12-ft air-conditioned concrete structure located approximately 30 feet from a residence. The grounding system was composed of ground rods at the corners of the structure which were bonded to the power system ground rod. Ground resistance between the monitoring system single-point ground terminal and remote earth was measured at about 3 ohms including the power ground.

The system, described in detail in the next section, was set to trigger when voltage on the ring conductor exceeded 100 V rms for at least 0.25 second or 250 V peak. The system surge sweep rates were initially set to 0.1 μs per point for the 548 pretrigger points and 2.0 μs per point for the remaining 1500 points giving a record length of 3055 μs. (The

last 24 bytes of each record were overwritten by system control information.) Near the completion of the study, the post-trigger sampling rate was reduced to lengthen the sampling window. In the event of an rms trigger, both sweep rates were 0.5 ms per point, giving a record length of just over 1 second. Reducing the sweep rate for 60-Hz events provided more appropriate recording of long duration data and also reduced the chance of needlessly filling the system storage due to extended ac activity.

A second recorder (designated Biomation No. 2 in Fig. 1) was connected to be internally triggered by, and to measure, current to ground for currents exceeding 50 A peak. This recorder required manual reset, and readout was via an oscilloscope. These manual characteristics were viewed as no handicap since large amplitude pulses were expected to occur infrequently. No pulses were recorded by this unit.

III. TRANSIENT MONITORING SYSTEM OVERVIEW

Experience with the analog system used at Washington[1] identified desirable monitoring system characteristics obtainable only with a digital design. The transient monitoring system (TMS) which resulted is illustrated schematically in Fig. 1. All system equipment is powered from an uninterruptible power source which protects the equipment and prevents loss of data during commercial power failures or transients. A single-point ground is utilized to prevent ground loops and extraneous signals within the system. A Biomation 8100 transient waveform recorder is controlled by a Digital Equipment Corporation PDP 11/10 computer through a special interface to acquire two channels of data—voltage on a ring conductor terminated to ground in a 1-megohm equivalent resistance (the resistance results from probes, attenuators, etc.) and short-circuit tip current to ground measured through a magnetic transformer device. The magnetic transformers used in this study were oriented to produce positive voltage at the associated recorder when the positive direction of current flow was out of the monitoring station.

The recorder was utilized in a dual channel, dual time base, pre-trigger mode resulting in timing such as that illustrated in Fig. 2. Calibration pulses are automatically injected into the system to provide checks on zero drift and gain characteristics. The system is triggered from a wideband, high-impedance, bipolar trigger unit capable of driving the recorder low-impedance external unipolar trigger. The overall trigger system is such that pulses exceeding the system trigger level for less than about 0.5 μs do not cause triggering.

A true rms detector system is used to sense longitudinal voltages associated with power system abnormalities which last at least 0.25 s

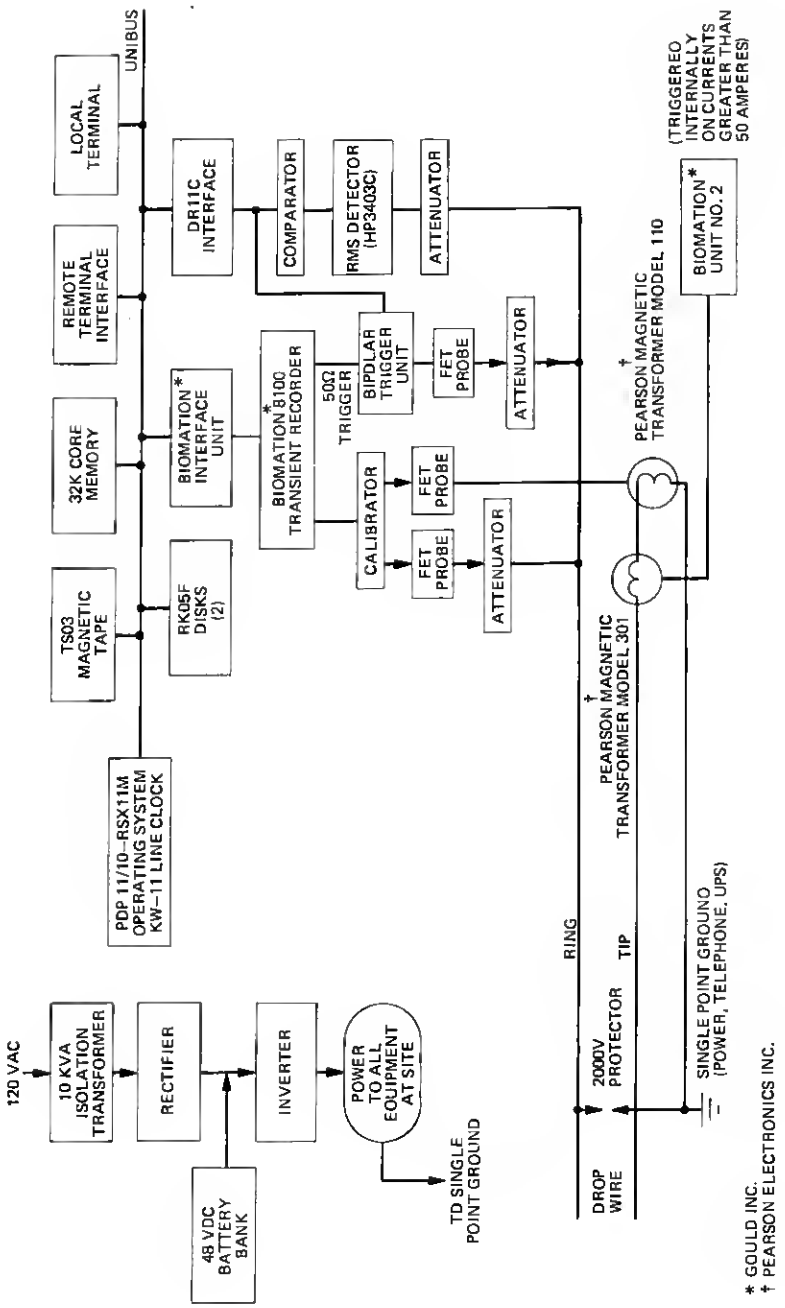

Fig. 1—System structure.

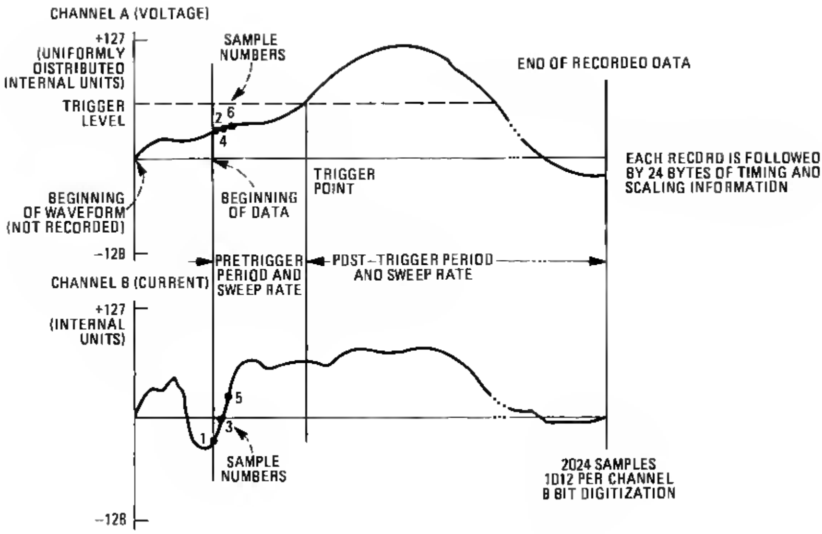

Fig. 2—Biomation sweep characteristics.

and exceed a predetermined rms value. During the study, this level was set at 100 V rms. Upon detection of an rms event, the system sweep rate is reset to a longer sample interval appropriate to power system events and the recorder is triggered. Data are transferred from the recorder to computer core memory, to disk storage, and finally to magnetic tape which is processed on an IBM 370 system. Local and remote terminals provide the ability to check system status as well as to alter system characteristics. The system provides for storage of 2400 events on disk and 2000 events on magnetic tape before manual intervention is required, a capacity which is adequate to record several severe storms.

IV. TIMING CONSIDERATIONS

The system contains sufficient core memory to allow accumulation of six records with a 5.0-ms dead period occurring between the end of each recorder sweep and rearming of the recorder by the computer. After each third sweep, data are transferred to the computer disk. If a high input data rate occurs and the six memory buffers are full, data recording ceases until three sweeps are transferred to disk. Under these saturation conditions, an average of 26 ms must elapse between the end of a recorder sweep and beginning of the next sweep. The net result is that the system can acquire up to six components (strokes) of a lightning flash if they are separated by at least five ms. Beyond this, loss of some stroke components may occur. As the median time between strokes is about 60 ms,[2] the minimum time between strokes

is about 10 ms, and the mean number of strokes per flasb is about 2.5, the resulting loss of data is not considered significant.

V. SITE ACTIVITY

The system was activated on June 9, 1978 and was turned off on December 9, 1978. The Greenville area experiences an average of 40 thunderstorm days (days on which thunder is heard at a specified location) annually. In 1978, the Greenville weatber bureau reported 35 thunderstorm days, 16 of which occurred prior to June 9 and 19 of which occurred during the monitoring period. After several instances of high monitoring system activity, calls to the local repair service bureau verified that there bad indeed been lightning activity in the Cleveland area. A thunderstorm detection device at the site, though fully operational only during the first few weeks of the study, also indicated local thunderstorm activity on days when the TMS recorded large numbers of events. It is believed that from system installation to the last thunderstorm day reported by the weather bureau on October 13, nearly all the system recordings were caused by lightning. Altbough the Greenville weather station is some 30 miles from Cleveland, for the purpose of calculating strokes per thunderstorm day it is assumed that the 19 thunderstorms recorded at the weather station are representative of activity at the monitoring site. It should be noted that total thunderstorm days are used only for calculating per-storm quantities.

As discussed above, good correlation between recorded transients and thunderstorm days continued until mid-October when the number of recorded surges reached a very low level. Soon, however, activity began to increase, but the number of events per day, the duration of the waveforms, and the distribution of hour of occurrence had changed markedly. Shortly thereafter, Southern Bell received reports of noise from customers along the cable route used by the monitoring station. After investigation, Southern Bell personnel located a faulty automatic oil switch in a power system capacitor bank which, when repaired, led to a marked decrease in monitoring activity for several days. Activity then slowly accelerated reaching a peak on December 6, 1978 when 820 pulses were recorded. A visit to the capacitor bank again revealed a sticking automatic oil switch. This was repaired on December 7, and the event count per day at the monitoring site dropped to five or less until site deactivation two days later. Induction in the area was reported to be 70–80 V rms to ground at the time of the first repair, and approximately 90 V rms at the latter repair. Such capacitor bank behavior was said to be common, occurring throughout the area every fall with the highest noise levels being reached under heavy load conditions between 8:00 and 8:30 PM. An analysis of the monitoring

site records for this period indicated 51 percent of the activity during the period of capacitor bank malfunction occurred between 8 and 9 PM and 61 percent occurred between 8 and 10 PM. It is important to note that, of the 27 times the system rms trigger was operated, 22 occurrences were prior to the period of capacitor bank malfunction, i.e., the capacitor bank malfunction did not produce the rms events reported.

VI. CLASSIFICATION OF LIGHTNING PULSES

As a result of the factors described in the previous section, it was possible to divide the data records into several categories and subcategories. The rms and capacitor bank records are discussed as appropriate, while the lightning pulses are described in this section. Records 1 to 2947 were recorded during the period of thunderstorm activity from June 9 through October 16. The 2387 valid lightning events (i.e., not calibration, rms, or test pulses) within this range could have been produced by a variety of mechanisms sucb as lightning hits to commercial power lines, lightning hits to the telephone loop, induced lightning pickup by the telephone loop, ground potential rises, etc. As examination of the records usually does not positively reveal their sources, the records acquired during this period, excluding those which activated the rms trigger, have been designated as "lightning" which should be interpreted as "most likely produced by a lightning-related mechanism."

The lightning records were categorized into flashes and strokes. A lightning flash typically consists of several well-defined strokes and is normally less than one second in duration.[2] Accordingly, lightning events separated by less than one second were considered to have been caused by strokes belonging to the same flash. As is the case in designating a particular event as lightning, it is impossible to assert that all events occurring within one second were physically associated with a given lightning flash. Since closely spaced pulses may produce thermal effects in terminal equipment which are different from those produced by the same pulses widely spaced in time, the above classification proves operationally useful despite its physical ambiguity.

VII. PEAK VOLTAGE

The peak voltage of an event was defined as the maximum voltage magnitude observed during the event. As first installed the two TMS channels were devoted to low and high current measurements. On August 2, 1978 the high current channel (which was capable of recording 1000 ampere events but had shown no activity) was converted to a voltage channel and was left in this configuration until the end of the study. As a result, 1087 lightning voltage records were obtained as opposed to the 2387 lightning current records. The peak voltage

distribution for all lightning events is shown in Fig. 3. It was found that 86 percent of the peak voltages were of positive polarity (i.e., that for 86 percent of the waveforms the highest voltage magnitude attained was of positive polarity). The distributions for first- and second-stroke lightning peak voltages, if plotted, could not be distinguished from the curve of Fig. 3 and have been omitted for brevity. It should be noted that a small percentage of the surges exceeded the system maximum of 1000 V, so that the distributions should be considered truncated at that level.

The lightning voltage distribution obtained in Cleveland is compared to similar data[1,3,4] in Fig. 4 where it is seen that the Washington, Connecticut, data are the most severe. Assuming 19 thunderstorm days occurred during the monitoring period at Cleveland, the average number of surges per thunderstorm day exceeding a given voltage was computed and is shown in Fig. 5. The first-stroke Cleveland data should be used when making comparisons against the other curves since the reset time of the systems used in previous experiments was on the order of one second and had limited capability to acquire multiple strokes. Again, the Washington data seen to be the most severe.

The peak voltage distribution of events attributed to the capacitor bank is shown in Fig. 6. The highest voltage due to this source was

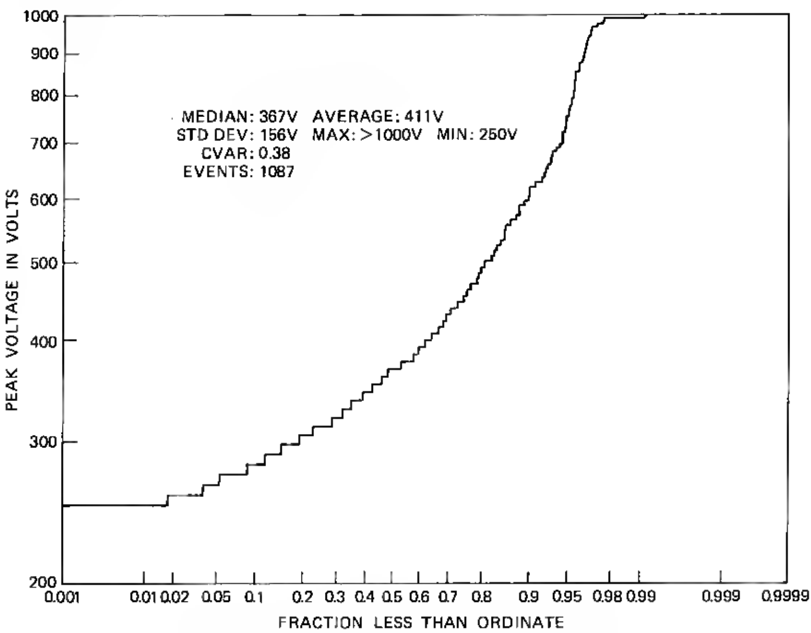

Fig. 3—Lightning peak voltage distribution.

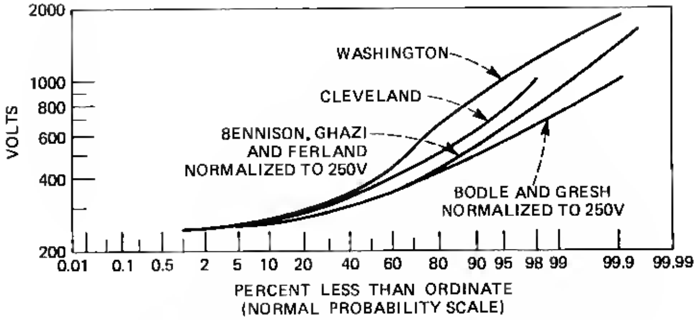

Fig. 4—Comparison of peak voltage data.

well below the system maximum and the coefficient of variation is much less than that associated with the lightning events.

VIII. PEAK CURRENT

Peak current magnitude is defined in a manner analogous to peak voltage magnitude. As indicated in Fig. 1, the measurement is of short

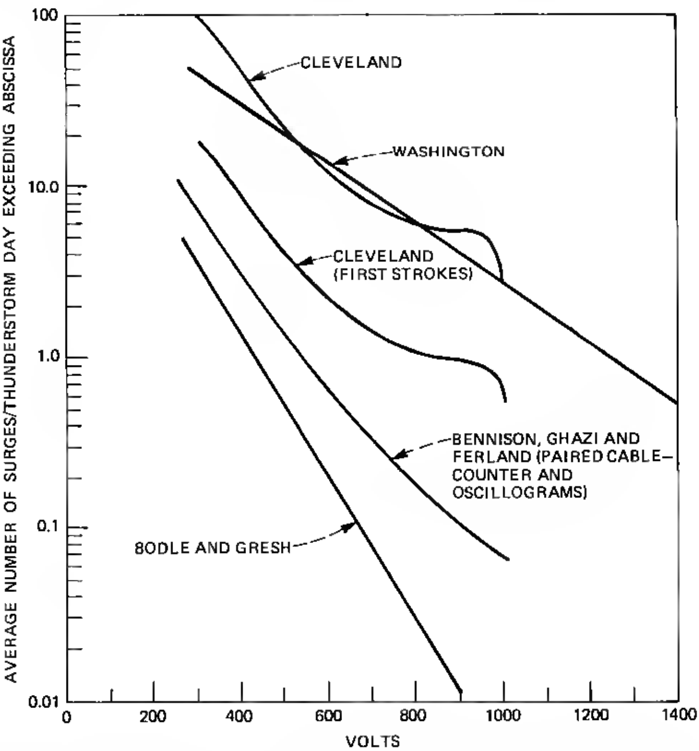

Fig. 5—Comparison of surges per thunderstorm day exceeding voltage thresholds.

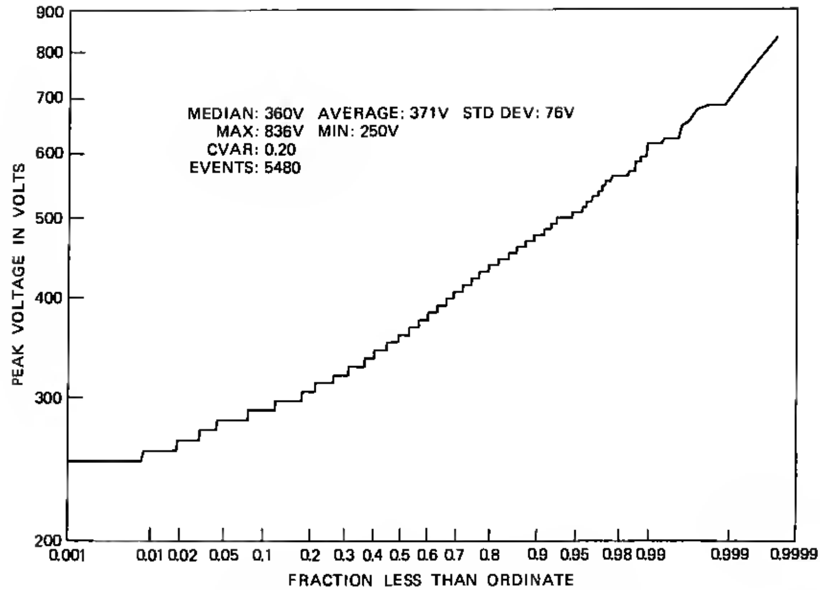

Fig. 6—Capacitor bank peak-voltage distribution.

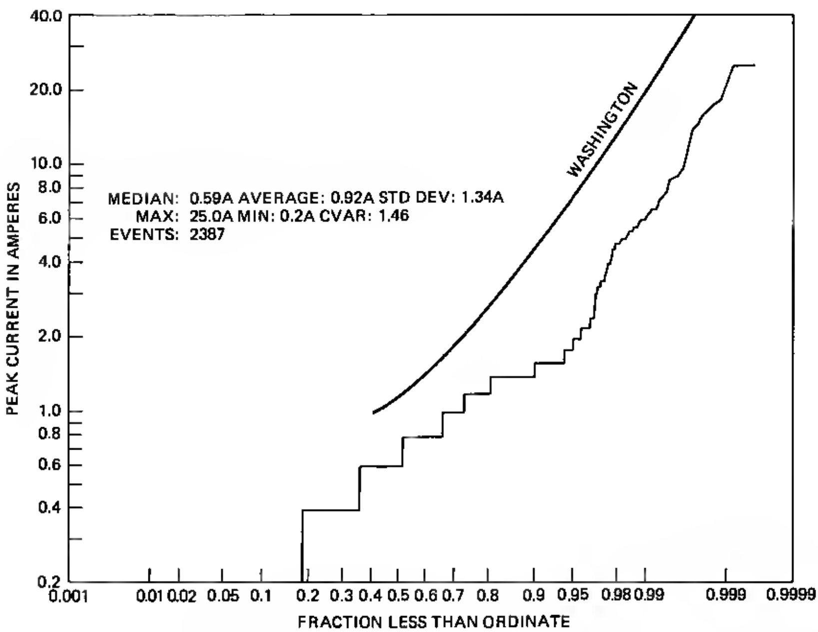

Fig. 7—Lightning peak-current distribution.

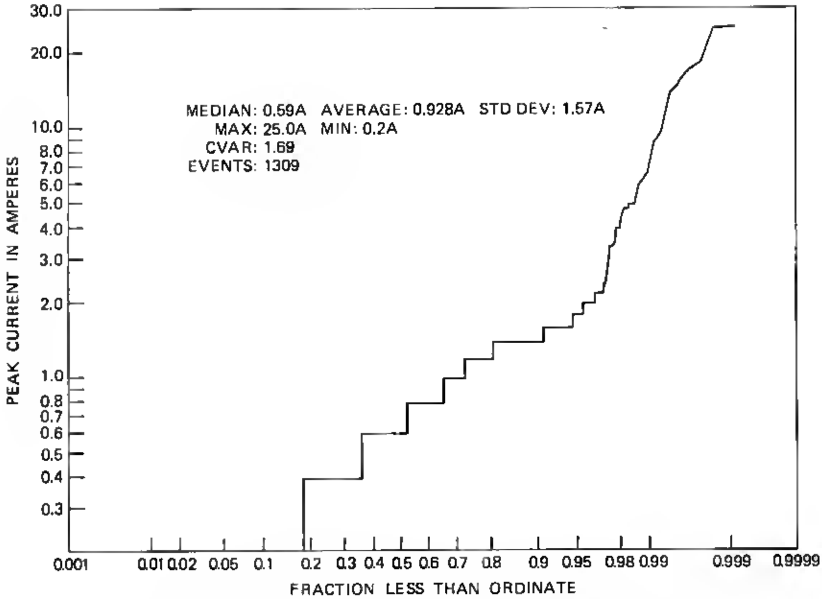

Fig. 8—Lightning first-stroke, peak-current distribution.

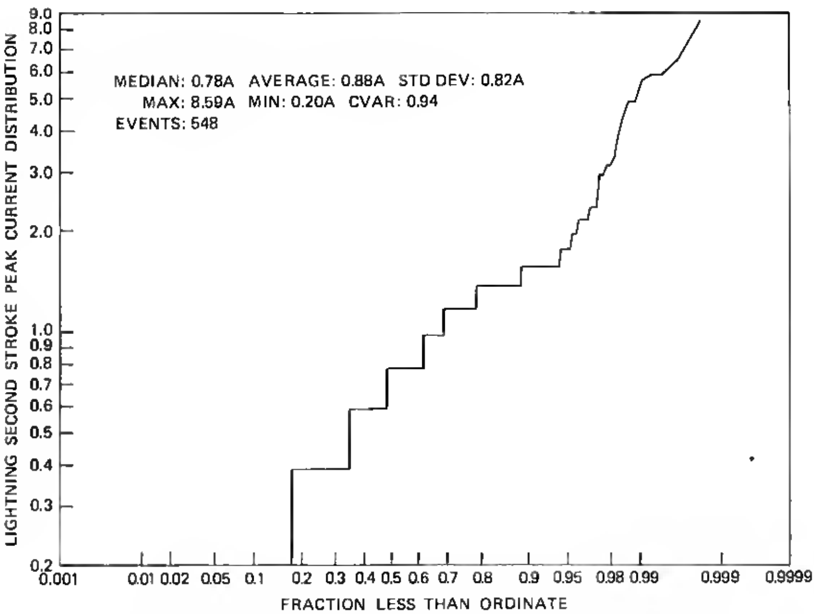

Fig. 9—Lightning second-stroke, peak-current distribution.

circuit tip current to local ground as sensed by a wide-band transformer pickup for events during which the ring voltage to ground exceeded 250 V. Lightning peak current distributions are shown in Figs. 7, 8, and 9. The steps in the current distributions are due to the discrete recorder amplitude bins of about 0.195 A and the fact that currents of peak magnitude comparable to 0.195 A were frequently recorded. For instance, there is a 100 percent change between the amplitude bins at 0.195 and 0.390 amperes. While also present in the voltage data, the peak voltage threshold imposed by the trigger level of 250 V makes the discrete nature of the distribution much less noticeable. In this case, the amplitude bins of about 8 V combine with a 250 minimum

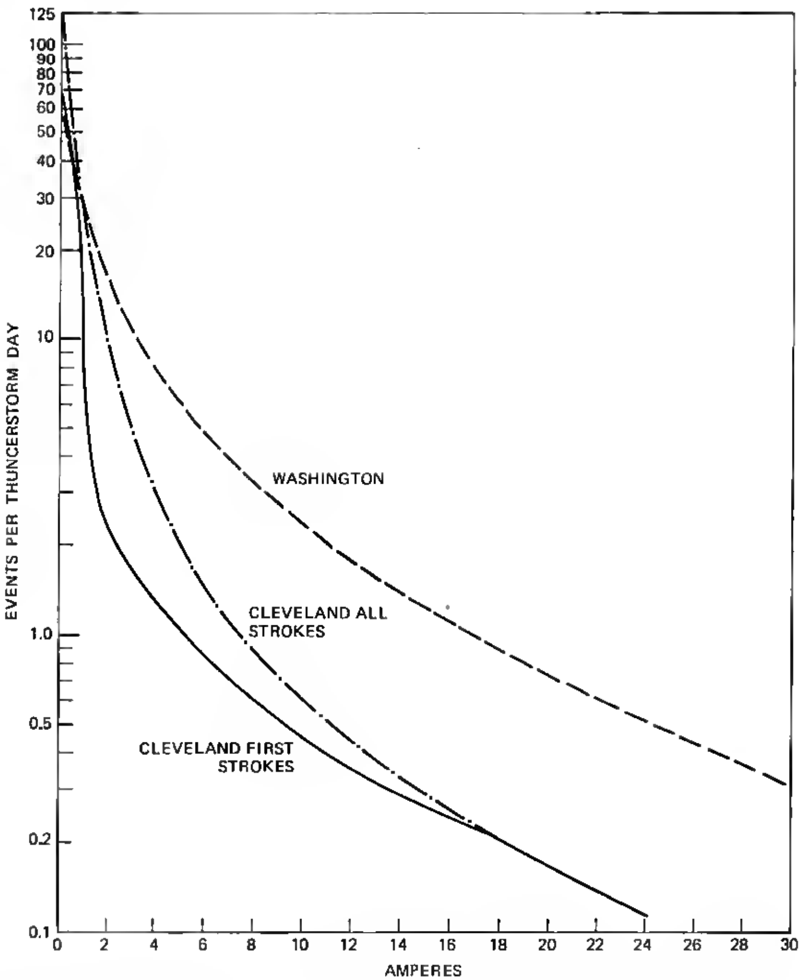

Fig. 10—Average number of events per thunderstorm day exceeding current of ordinate.

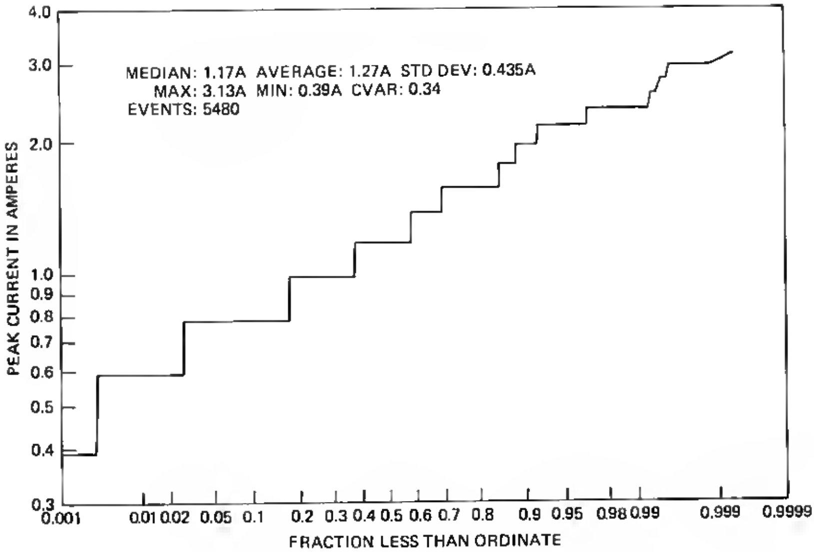

Fig. 11—Capacitor bank peak-current distribution.

peak signal to give a gap of 3 percent between the two lowest voltage bins. It was found that 61 percent of all lightning peak currents were of positive polarity.

As can be seen, the largest currents occurred among the group

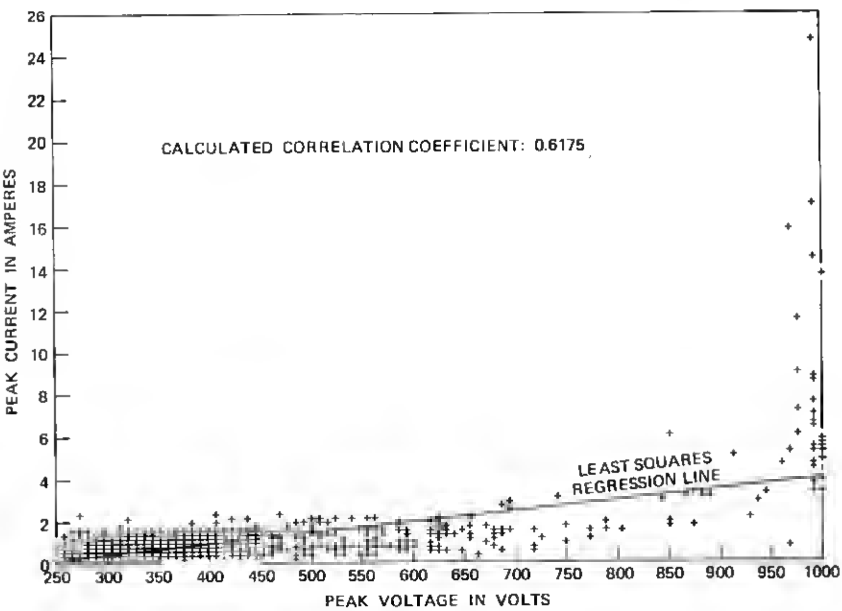

Fig. 12—Lightning peak *V-I* scatter plot.

identified as first strokes. The peak current distribution from Washington, Connecticut, which is also plotted in Fig. 7, is seen to be more severe than the present data. In Fig. 10 it is seen that, for currents exceeding about 1 A, Washington averaged more events per thunderstorm day than Cleveland.

The peak current distribution for events associated with the capacitor bank is shown in Fig. 11. The distribution is considerably better behaved than the lightning current distributions and may be reasonably approximated as lognormal.

IX. PEAK MAGNITUDE SCATTER PLOTS

It is natural to suspect that events producing large peak voltages will be associated with large peak currents. To investigate this possibility, the scatter plots of Figs. 12 to 15 were prepared. A word of caution is in order concerning such plots—because of quantization effects and graphic system characteristics, only a finite number of plotting coordinates are available, and a given event will be assigned to the nearest of these points. For this reason, a given point in a scatter plot may represent more than one event recorded by the monitoring system. Figure 12 shows peak voltage-peak current magnitude pairs for lightning events as well as the least-squares regression line. The square of the sample correlation coefficient, which is known as the

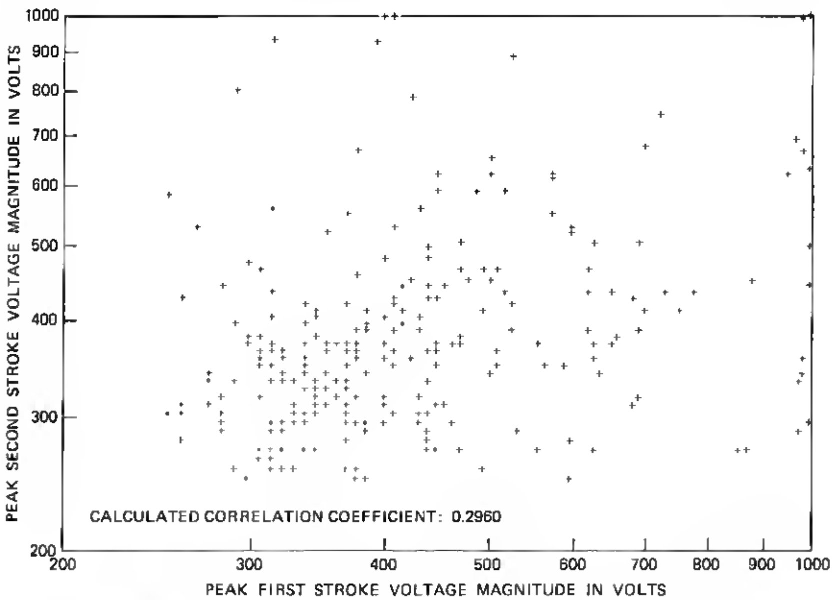

Fig. 13—First-stroke, second-stroke, peak-voltage scatter plot.

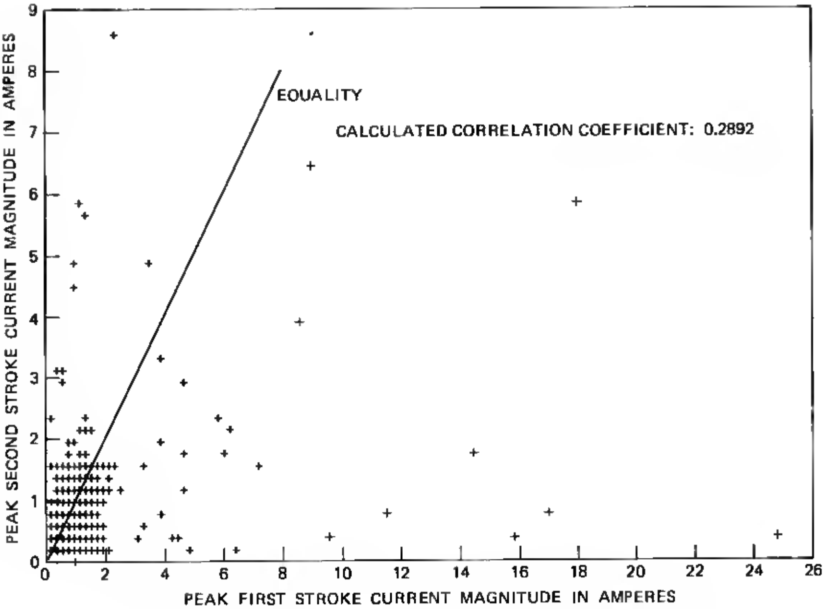

Fig. 14—First-stroke, second-stroke, peak-current scatter plot.

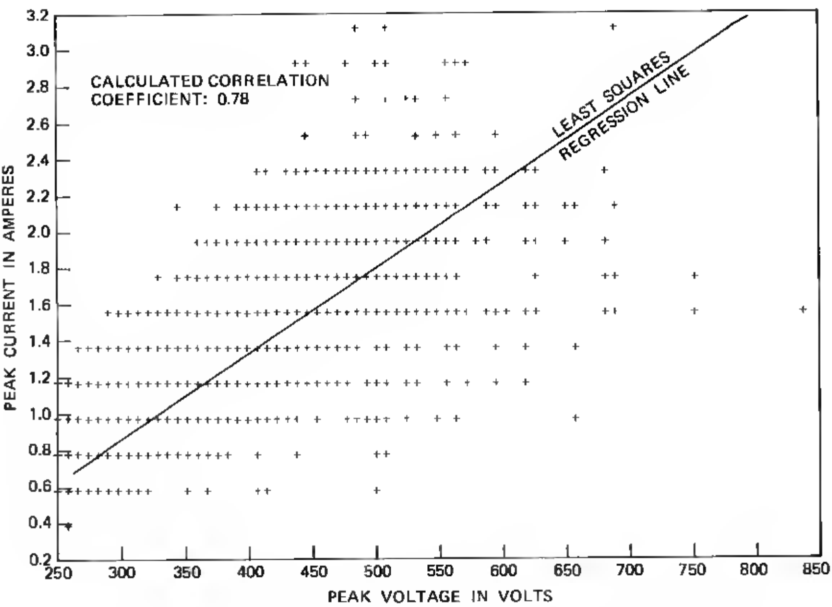

Fig. 15—Capacitor bank peak *V-I* scatter plot (magnitudes).

coefficient of determination, provides an estimate of the percentage of overall variation in the dependent variable which can be attributed to variations in the independent variable—in this case, only about 38 percent. Although a trend toward higher currents at higher voltages exists, a least-squares linear relationship is not quantitatively useful. Plots of first-stroke vs second-stroke voltages and currents, Figs. 13 and 14, show even less relationship. It is useful to note that larger currents generally occurred on first strokes but that such a trend was not apparent in the voltage data. The scatter plot for capacitor bank events (Fig. 15) indicates more dependence between voltage and current than was observed with lightning.

X. RATE OF RISE

As discussed in Ref. 1, a generally accepted definition of rate of rise exists for double exponential waveforms. For the more complex waveforms observed on loops, a more general definition was developed and continues to be appropriate. The voltage rate of rise at 300 V, for instance, was defined in Ref. 1 as the waveform derivative at the first crossing of 300 V. This definition was also adopted for the TMS data processing but, because of the quantization of time and amplitude in the TMS output, it was necessary to mathematically condition the data.

Numerical calculation of derivatives is a difficult task, particularly for data which are discrete in time and quantized in amplitude. If the

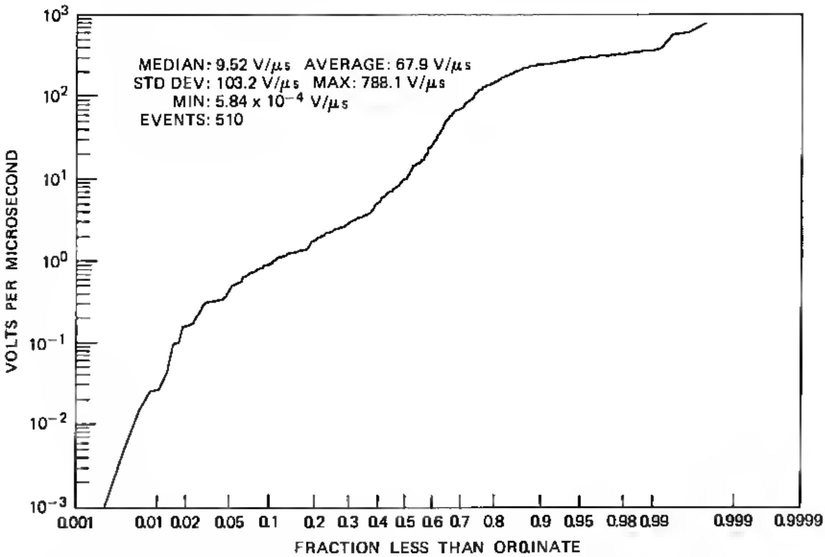

Fig. 16—Lightning first-stroke voltage rate of rise at first crossing of 300 V.

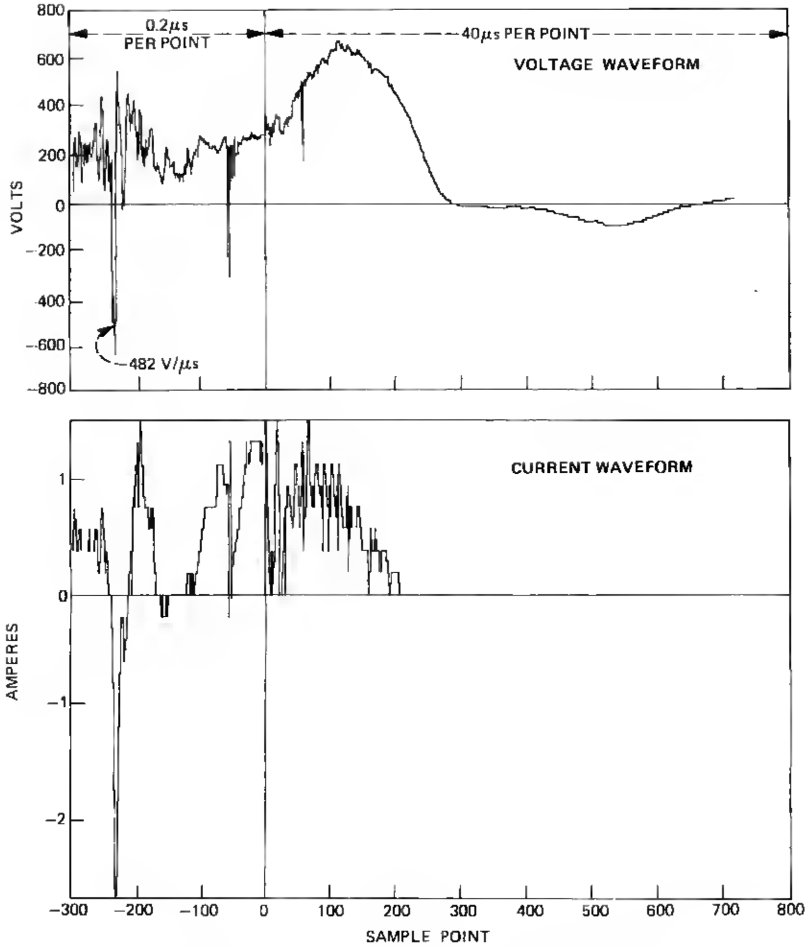

Fig. 17—Waveform containing high rate of rise transient.

quantizing error is large compared to the true change between samples, simple numerical techniques may lead to huge errors in results. If excessive data smoothing is used, again unnecessary errors may result. For the task at hand, it was decided to bracket the time sample point at which the derivative was desired, to fit splines[5,6] (interpolatory and B-spline) to the data, and to evaluate the derivative in a variety of ways to test for consistency of results. The approach adopted was to use interpolatory splines at rates of rise up to 300 V per μs and least-squares B-splines at higher rates of rise where more sophisticated techniques became necessary.

The results are indicated in Fig. 16. The high rate of rise events in

the upper tail of the distribution result from narrow voltage impulses superimposed on the basic waveform, as illustrated in the waveform of Fig. 17. Because of the considerable smoothing employed, impulses contributing to Fig. 16 must have been of considerable amplitude and existed for several sample points, i.e., they appear to be real and not artifacts of the digitizing process. These impulses, possibly produced by protector operation on adjacent pairs or by arcing in the cable plant, were detected only because of the system pretrigger capability and wide recording bandwidth since they were beyond tbe bandwidth of the recorder trigger circuitry. Each voltage impulse caused a simultaneous impulse in the short-circuit current waveform. Although the energy associated with such impulses is small, they may not be sufficiently limited in magnitude by conventional primary protection devices such as gas tubes, and appropriate secondary protection schemes may be required in sensitive terminal equipment.

Because the digitizing process used to process the analog records from Washington, Connecticut, yielded at most 50 points per record, the data from that site would not have revealed such impulses if they had been present. In an attempt to approximately compare the Cleveland data with the Washington data and the results of other investigations, derivatives were also calculated at the system trigger point where such noise pulses did not occur because of the reduced bandwidth of the system trigger. This distribution, obtained at the nominal 250-V trigger point and based on first strokes only, is shown in Fig. 18.

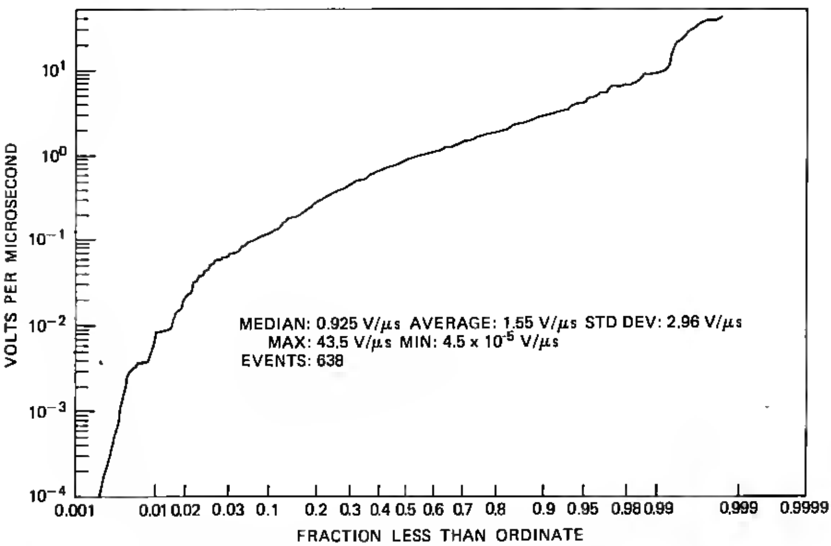

Fig. 18—Lightning voltage rate of rise distribution at trigger point.

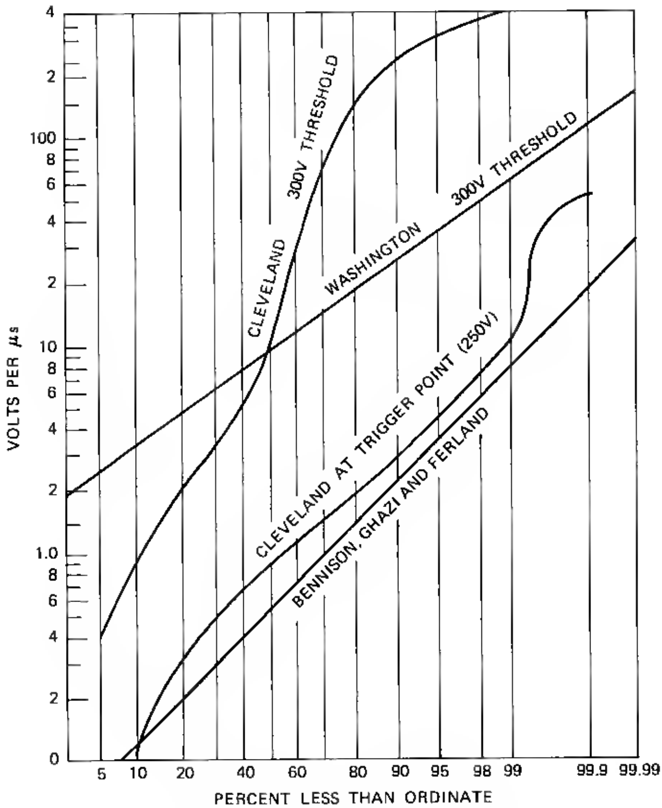

Fig. 19—Comparison of rate of rise data.

In Figure 19 it is seen that the trigger point data are comparable to voltage rate of rise data obtained by Bennison[3] but less severe than voltage rate of rise data obtained at Washington.[1] Lightning current rate of rise data is shown in Fig. 20, where no attempt was made to remove narrow impulses.

The rate of rise distributions derived from the capacitor bank waveforms are shown in Figs. 21 and 22. These pulses also contained spikes, reinforcing the belief that the spikes were caused by protector block operation or arcing in the cable plant rather than through a mechanism peculiar to lightning events.

XI. ENERGY

As described in Ref. 1, several integrals related to energy are of interest. The integrals $\int v^2\,dt$ and $\int i^2\,dt$ are used to compute energy dissipated in a resistive load while $\int |v|\,dt$ and $\int |i|\,dt$ relate to circuitry

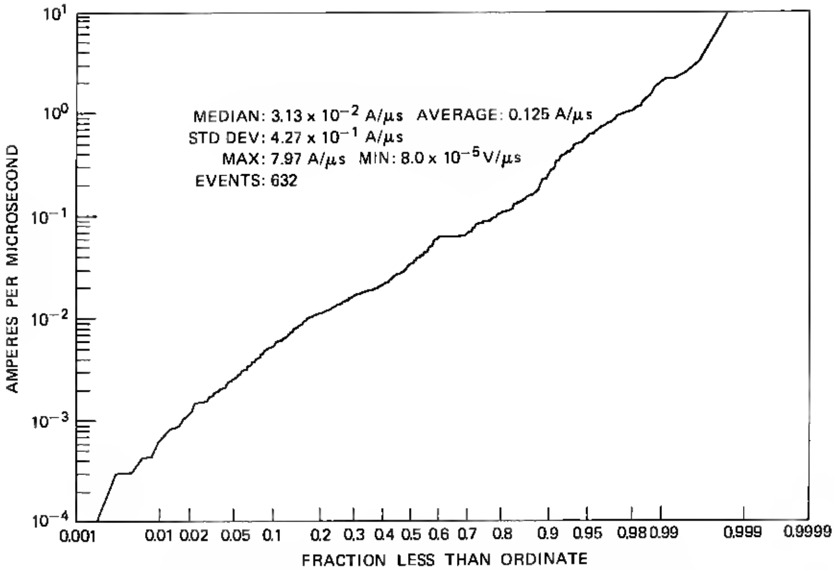

Fig. 20—Lightning current rate of rise at first crossing of 1 A.

in which i and v respectively are held constant. The distributions of these quantities are given in Figs. 23 through 26 along with data available from Washington, Connecticut. Also shown in Figs. 27, 28, and 29 are scatter plots of energy versus peak voltage and current.

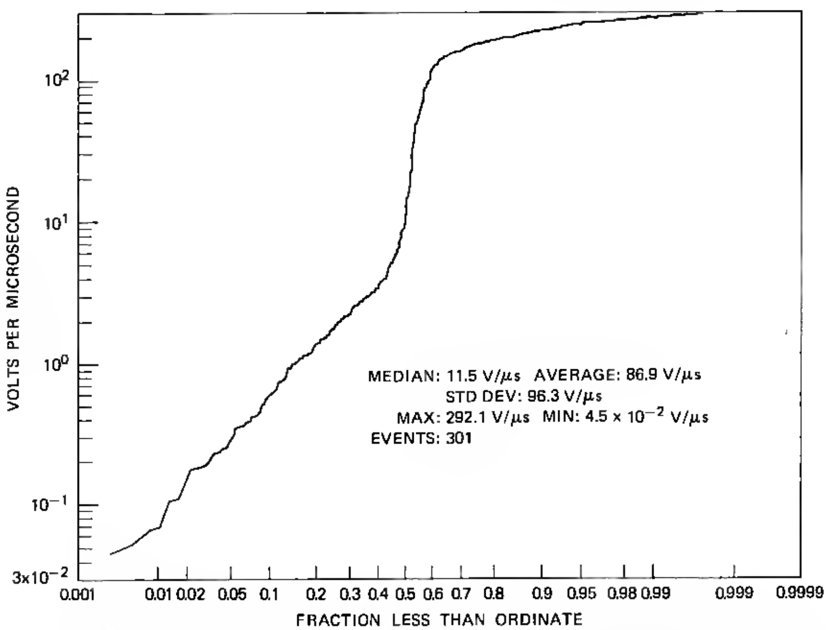

Fig. 21—Capacitor bank voltage rate of rise at first crossing of 500 V.

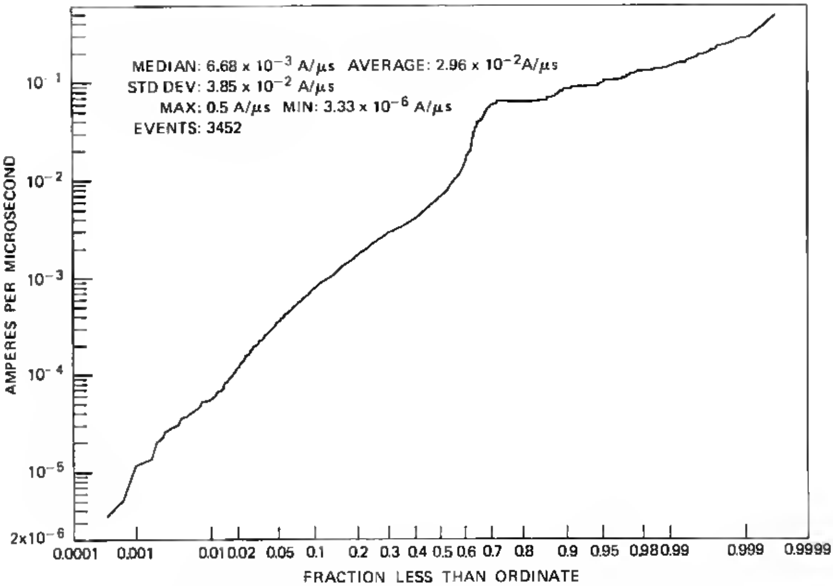

Fig. 22—Capacitor bank current rate of rise at first crossing of 1 A.

From the positive correlations, it is seen that there is a trend toward increasing energy with increasing magnitude, a trend which is most visually apparent in the current plot of Fig. 29. It is also demonstrated in the figures that, for a given event, an exponential wave of the same

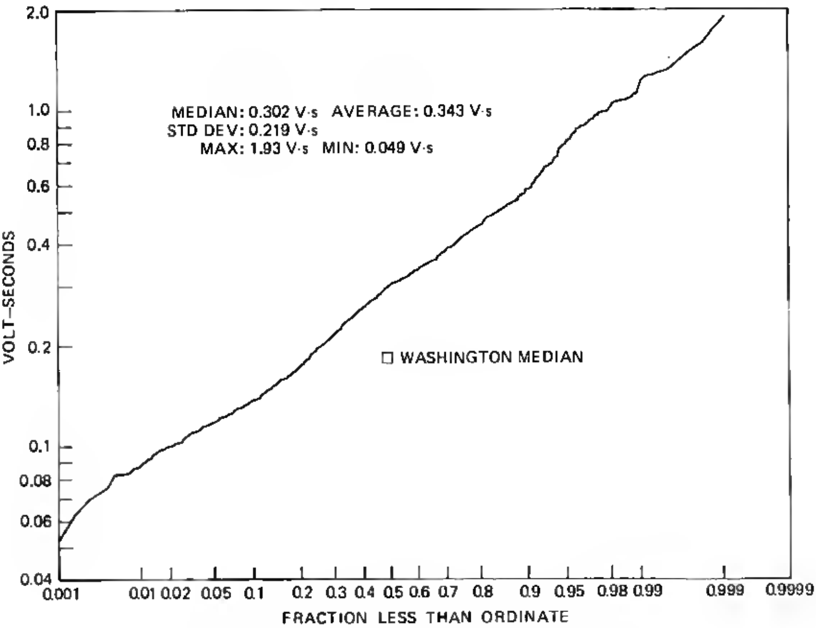

Fig. 23—Lightning $\int |v|\, dt$ distribution.

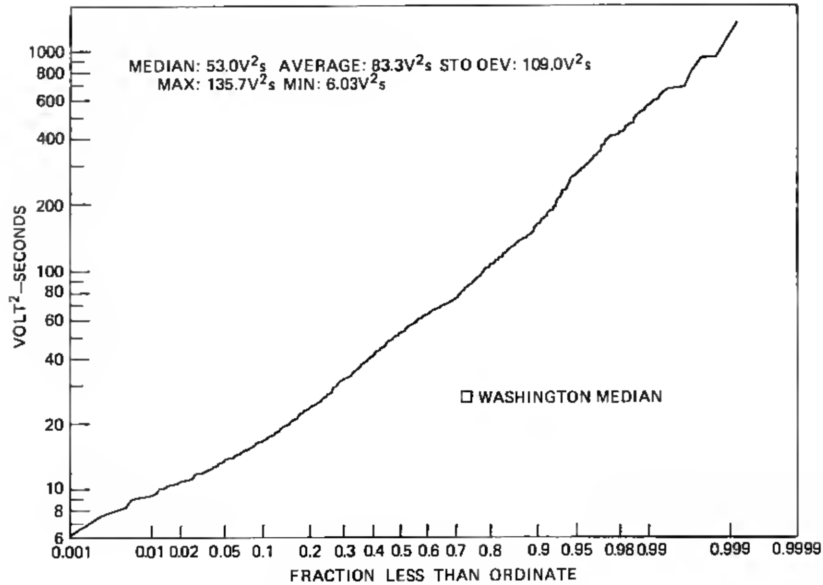

Fig. 24—Lightning $\int v^2\,dt$ distribution.

peak amplitude and with a 1000 μs decay to half value would contain more voltage "energy" than the given event in most cases and would always contain more current energy.

A correlation of about 0.4 between peak voltage and energy was

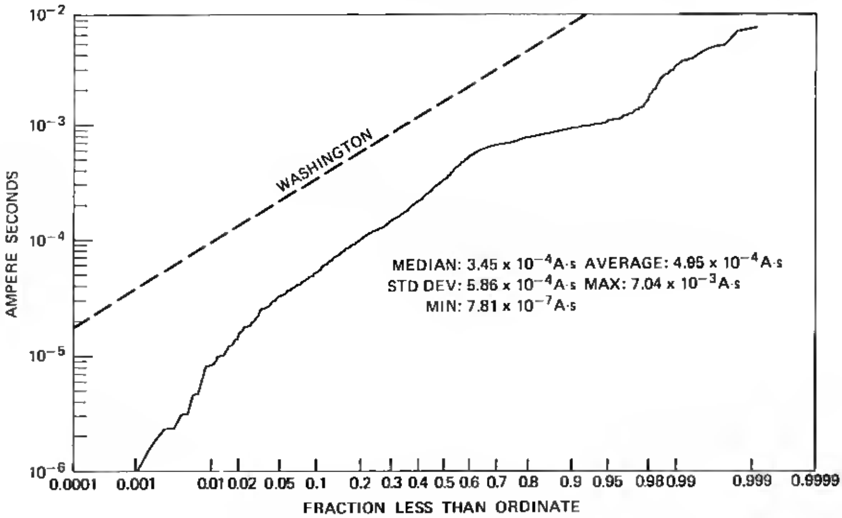

Fig. 25—Lightning $\int |I|\,dt$ distribution.

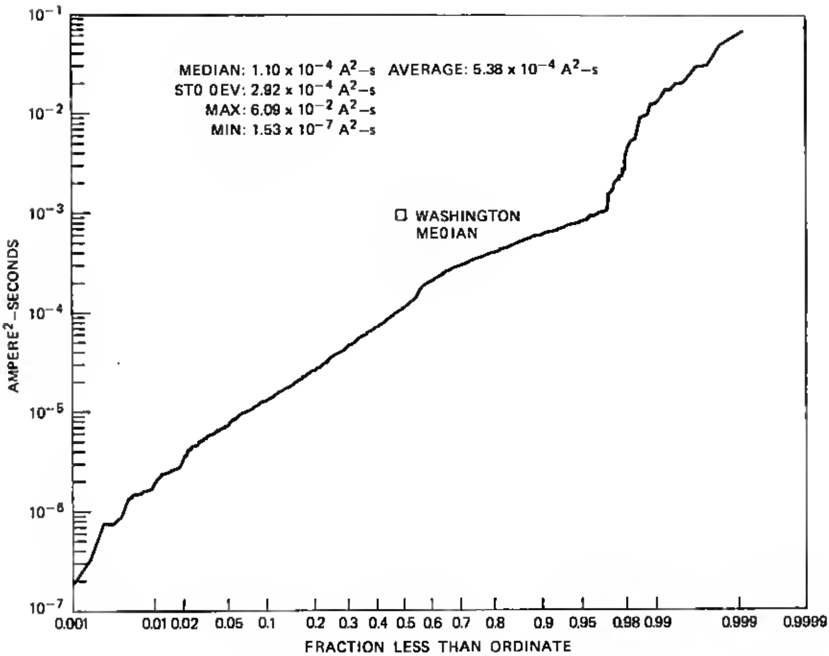

Fig. 26—Lightning $\int I^2\,dt$ distribution.

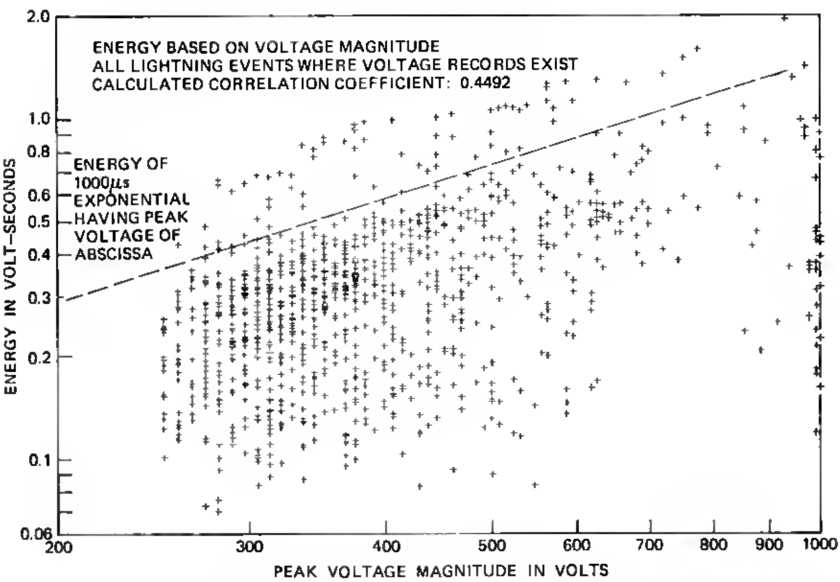

Fig. 27—Energy-peak voltage scatter plot.

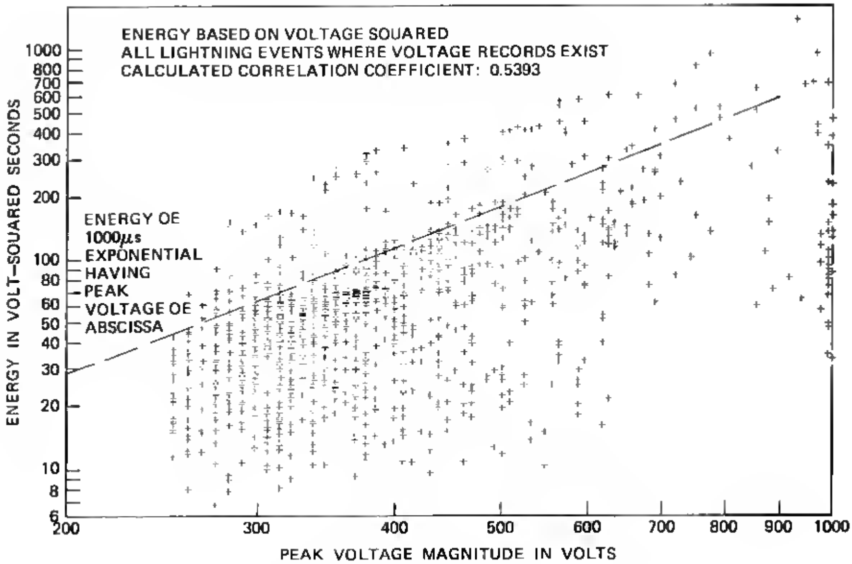

Fig. 28—Energy-peak voltage scatter plot.

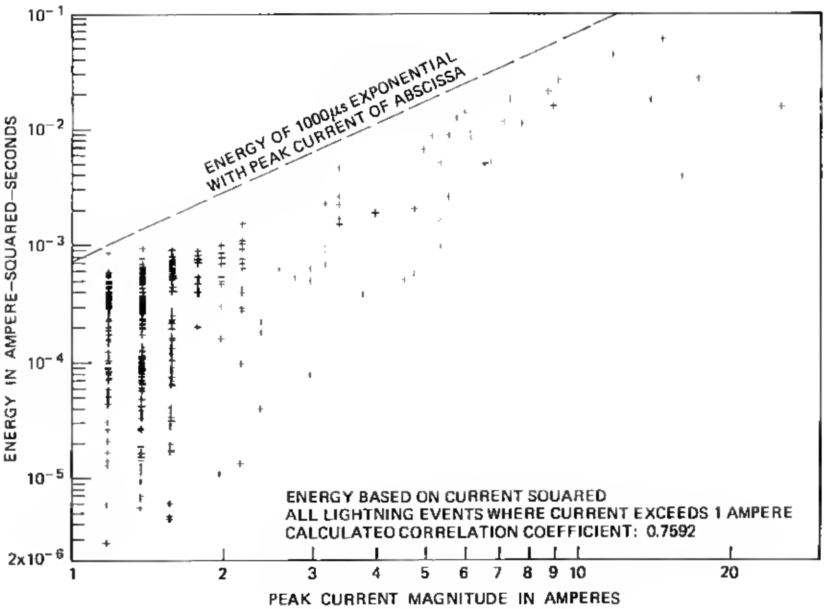

Fig. 29—Energy-peak current scatter plot.

found in Washington, Connecticut,[1] vs 0.45 and 0.54 in Figs. 27 and 28. Prior to the data reduction from Washington, it had been expected that the correlation between peak current and energy would be similar to that of peak voltage and energy. Instead, it was found to be close to zero in Washington versus 0.76 in Cleveland. Corresponding plots for capacitor bank events are not given since, in most cases, the duration of these events exceeded the measurement time window.

XII. DECAY TIME

For a simple exponential wave $A\exp(-t/\tau)$, the decay time (to half value) T_H is given by $T_H = 0.693\tau$, where τ is known as the decay time constant. For the complex waves recorded in Cleveland, decay time constants can be defined in terms of exponential waveforms having the same peak amplitude and equivalent energy as the complex waveform. As shown in Ref. 1, this leads to

$$\tau_{\text{equiv }1} \triangleq \frac{2}{x_p^2}\int_0^\infty x^2(t)\,dt \qquad \text{(based on amplitude squared)}$$

and

$$\tau_{\text{equiv }2} \triangleq \frac{1}{x_p}\int_0^\infty |x(t)|\,dt \qquad \text{(based on magnitude),}$$

where x represents voltage or current and x_p represents the peak amplitude. The equivalent decay time (to half value) is again 0.693 times the decay time constant.

The decay time distributions are given in Figs. 30 to 36. Information from other studies is given for comparison where available. Scatter plots comparing voltage-based decay times are given in Fig. 32, and the corresponding plot for current in Fig. 35. Although equality is not attained, a linear relationship between quantities on each plot is apparent with the square-based calculations giving the longest decay times. The correlations between decay time and peak voltages or currents were found not to exceed 0.08. As discussed in Ref. 1, this was expected because of the normalization contained in the definition of decay time. The current decay times were only mildly related to and for the most part shorter than the corresponding voltage decay times as indicated in Fig. 36. This behavior was also apparent from visual examination of voltage-current waveform pairs. The voltage decay time distribution reported by Bodle and Gresh[4] from the five-mile cable at Mount Freedom closely approximates that obtained from the Cleveland voltage-squared data. The data reported by Bennison, Ghazi, and Ferland indicate considerably longer decay times than any

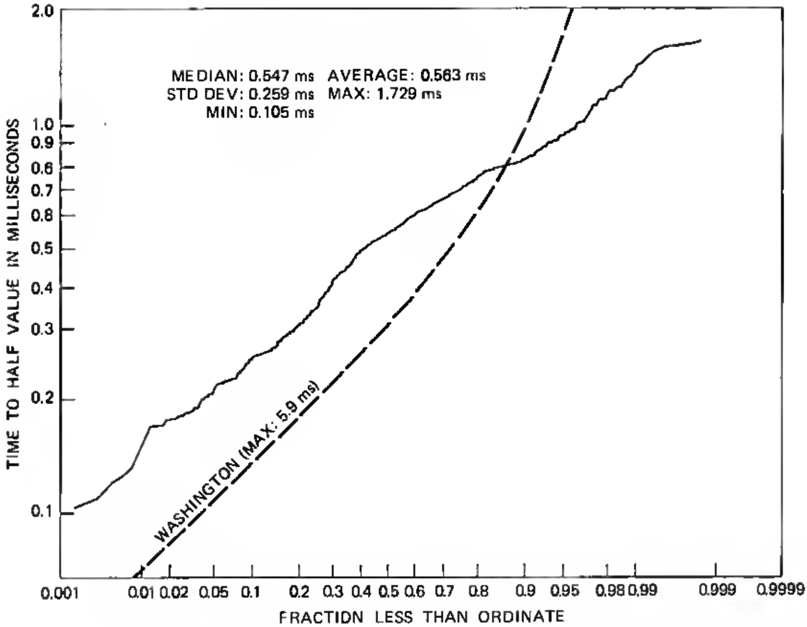

Fig. 30—Lightning voltage decay distribution based on voltage magnitude.

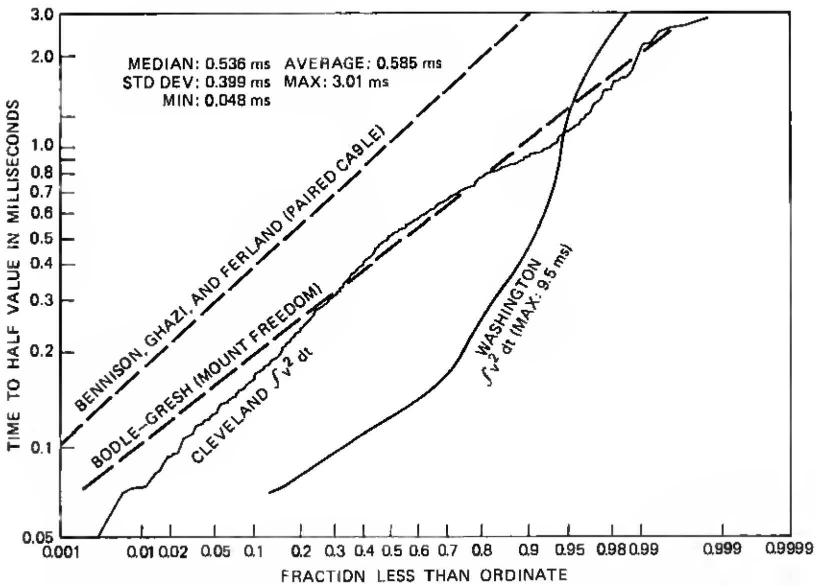

Fig. 31—Lightning voltage decay time distribution based on voltage squared.

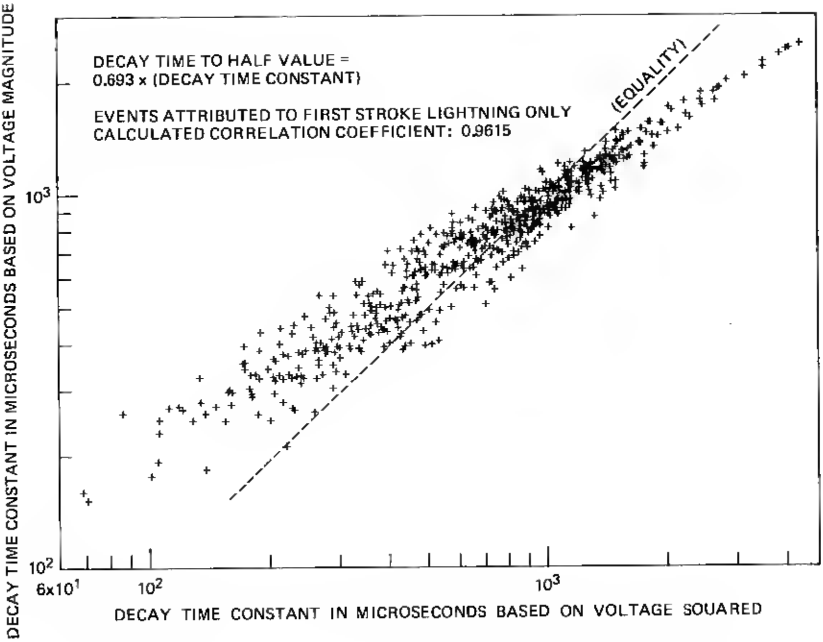

Fig. 32—Voltage decay time (magnitude) vs decay time (squared) scatter plot.

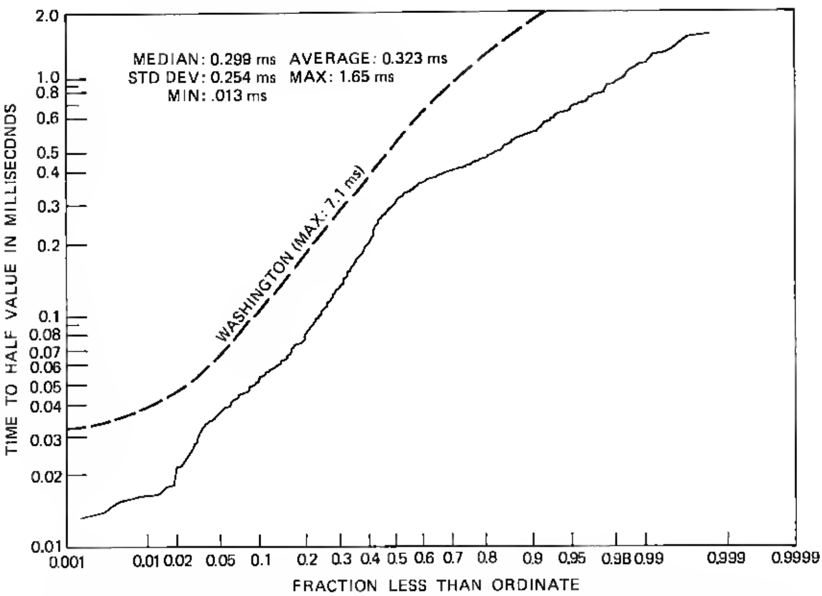

Fig. 33—Lightning current decay time distribution based on current magnitude.

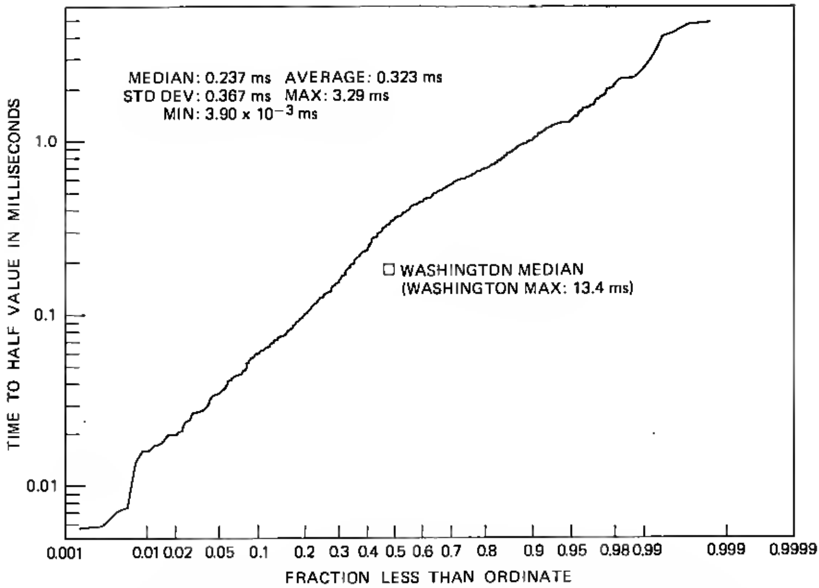

Fig. 34—Lightning current decay time based on current squared.

of the other distributions. The 1-ms decay time which has been widely regarded as encompassing 90 percent of all lightning surges in paired cable still appears appropriate based on the Cleveland data. It should be noted that the longest decay time observed at Cleveland was 3.3 ms.

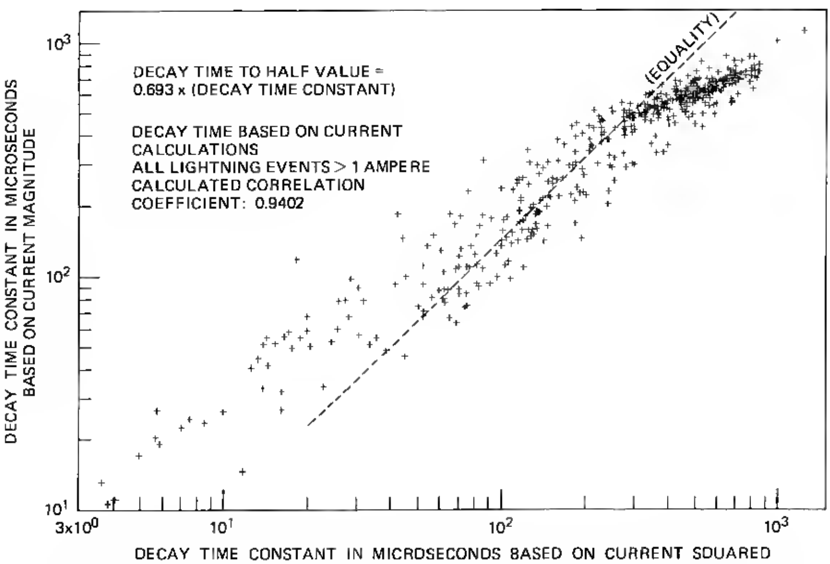

Fig. 35—Current decay time (magnitude) vs decay time (squared) scatter plot.

Decay time was not computed for the capacitor bank events since many of them continued well beyond the recorded data. Data records were extended from 3 ms to 7, 14, and finally to 144 ms before encompassing the bulk of capacitor bank events. It can be said that the capacitor bank events were primarily repeated damped sinusoids with a damping frequency of a few kilohertz such as illustrated in Fig. 37, but occasionally contained short-term sinusoidal activity at 60 Hz.

XIII. STROKES PER FLASH, INTERARRIVAL TIME, AND TIME OF OCCURRENCE

A lightning flash is typically composed of several closely spaced components called strokes. As discussed in Cianos and Pierce,[2] it is reasonable to assume that the total duration of a flash will rarely exceed 1 second, that the median time between strokes in a flasb is 60 ms, and that about 92 percent of all strokes are spaced greater than 16.67 ms apart. In this paper, it has been assumed that pulses occurring within a time interval of 1 second belong to the same flash. Although the system reset time was considerably shorter, the internal clock supplied time in units of 16.67 ms. When considering intra-flash events, time intervals less than 16.67 ms (recorded as 0) have been assigned as 8.34 ms for convenience of plotting.

The density of strokes per flash is shown in Fig. 38. The average number of recorded strokes per flash was 1.8. When comparing this to data given by Cianos and Pierce,[2] who report 2 to 3 strokes average per flash, it should be recalled that the TMS recorded a stroke only if

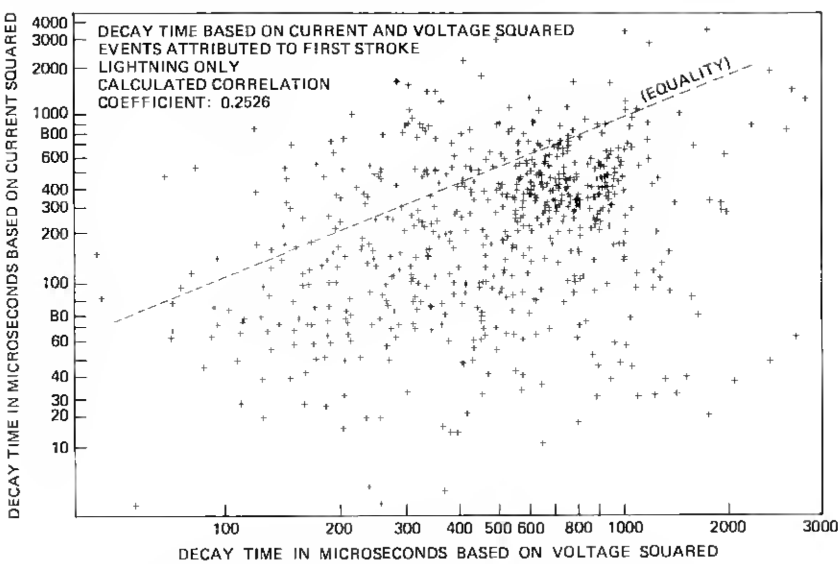

Fig. 36—Current decay time, voltage decay time scatter plot.

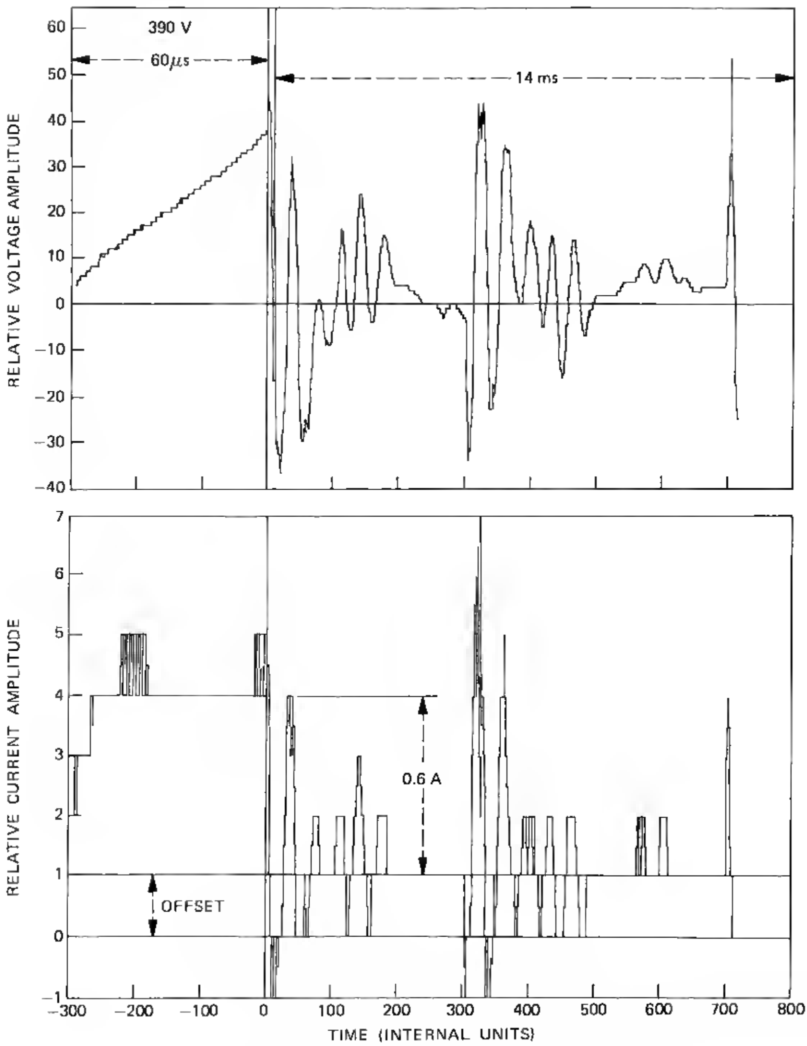

Fig. 37—Waveforms induced by malfunctioning capacitor bank.

its peak voltage exceeded 250 V so that all strokes occurring in a flash were not necessarily recorded. The density of flash time of occurrence is shown in Fig. 39, which shows that most events occurred between 3 PM and 4 PM E.D.S.T.

The flash interarrival time distribution is shown in Fig. 40 along with the Washington, Connecticut data[1] which are rather similar. The median time between flashes was found to be 52.9 seconds. Figure 41 gives the distribution of time between strokes within a flash along with a proposed model from Cianos and Pierce. The median time between

intraflash strokes was 83.4 ms. The quantization of time apparent in the Cleveland curve is due to the characteristics of the internal clock, as discussed above.

XIV. RMS EVENTS

As mentioned in the system description, an rms detector was used to detect voltages of 100 V rms or greater and to switch sampling rates to an interval more suitable to 60-Hz related data. For a periodic waveform, the thermal element employed by this instrument requires 0.25 second to heat from ambient to the temperature corresponding to

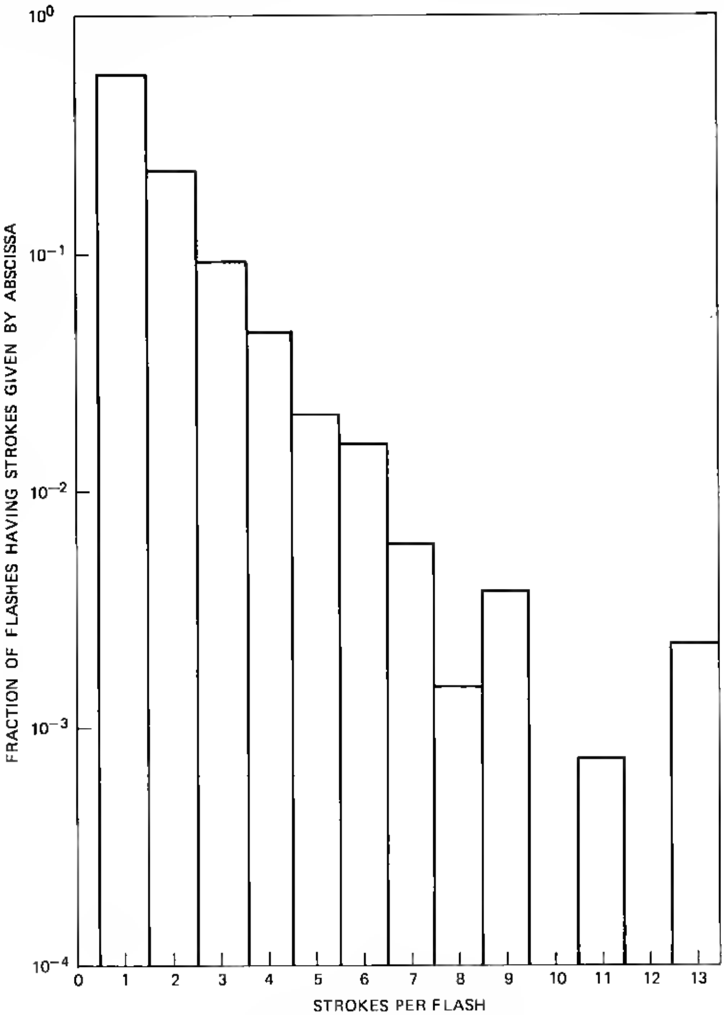

Fig. 38—Density of strokes/flash.

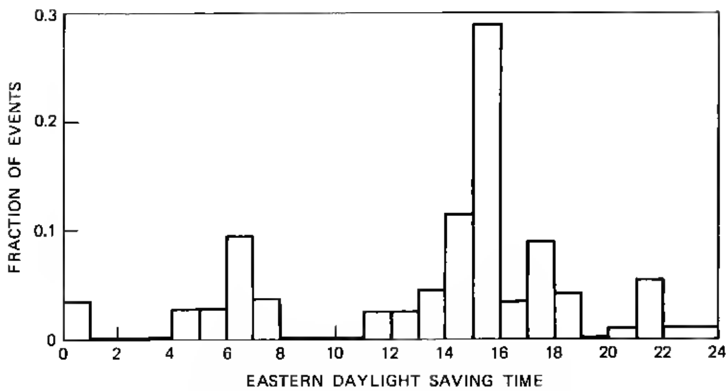

Fig. 39—Lightning time of occurrence.

the rms current flowing. The rms detector was activated 27 times during the study, producing records such as that shown in Fig. 42. A typical scenario was for induction voltages to momentarily reach 100 V rms causing the system to trigger, and then to fall to a lower level for the remainder of the sweep. If the voltage had been just less than 100 V rms for a period and then increased in amplitude, the time for the indicated output to exceed 100 V rms after the increase could be

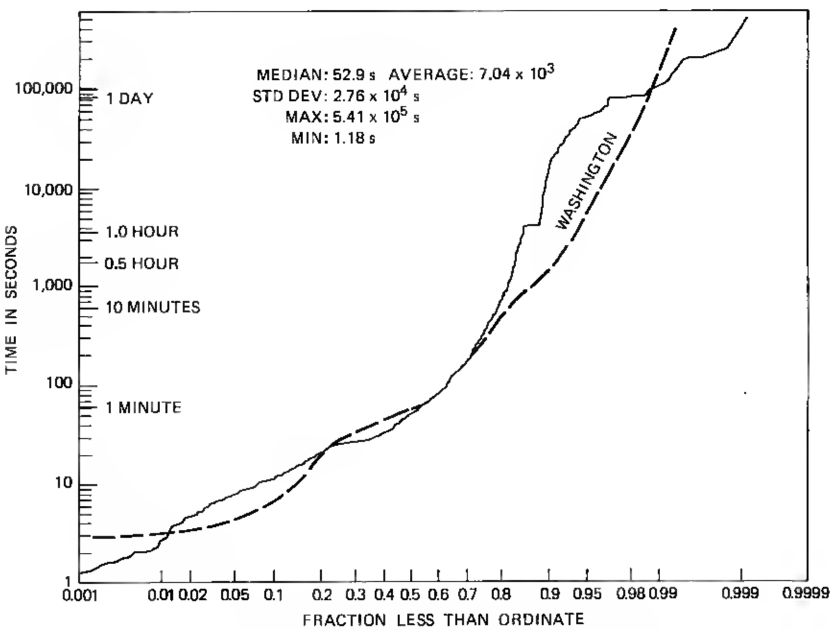

Fig. 40—Distribution of time between flashes.

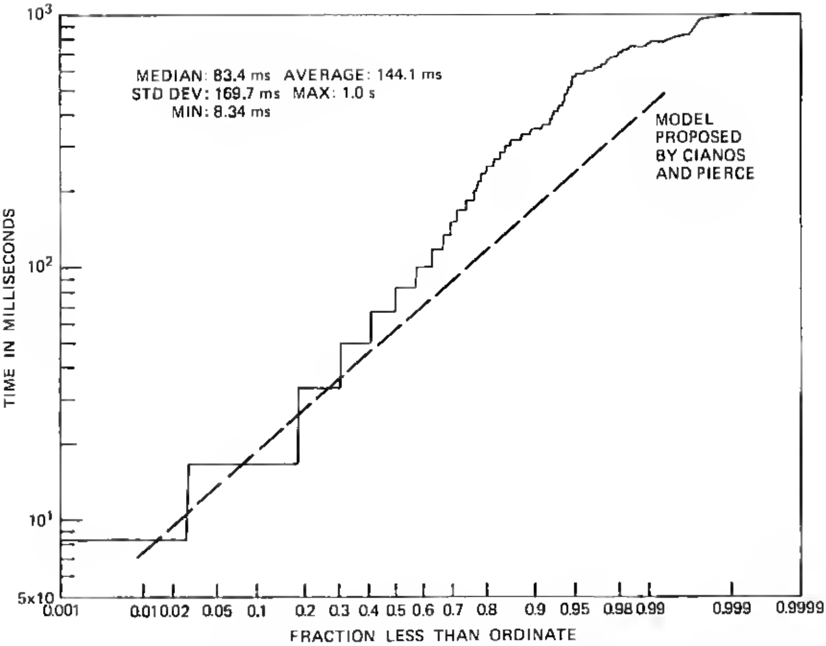

Fig. 41—Time between strokes within a flash.

less than 0.25 second. For the records obtained, the maximum voltage was 195 V peak and the maximum current was approximately 0.2 A peak; most of the currents did not exceed 0.1 A peak. At no time was the voltage at the end of an rms record sufficient to trigger an additional sweep. This implies that the maximum event duration was 1.26 second, 0.25 second to activate the sweep rate change followed by a 1.01 second record. By contrast, capacitor bank events, which did not trigger the rms detector, produced currents up to about 3 A peak. Shorter bursts of 60 Hz, up to seven cycles in length, were detected without activation of the rms trigger and produced currents up to 0.4 A peak with voltages to 508 V.

XV. SUMMARY AND CONCLUSIONS

A computer-based transient monitoring system was utilized to record open-circuit voltage and short-circuit current waveforms on a loop in Cleveland, South Carolina during the 1978 lightning season. The equipment operated reliably and met design objectives. Analysis of the data waveforms showed records attributed to lightning, to AC induction from power lines, and to disturbances resulting from power system capacitor bank malfunctions.

Both oscillatory and approximately exponential lightning waveforms

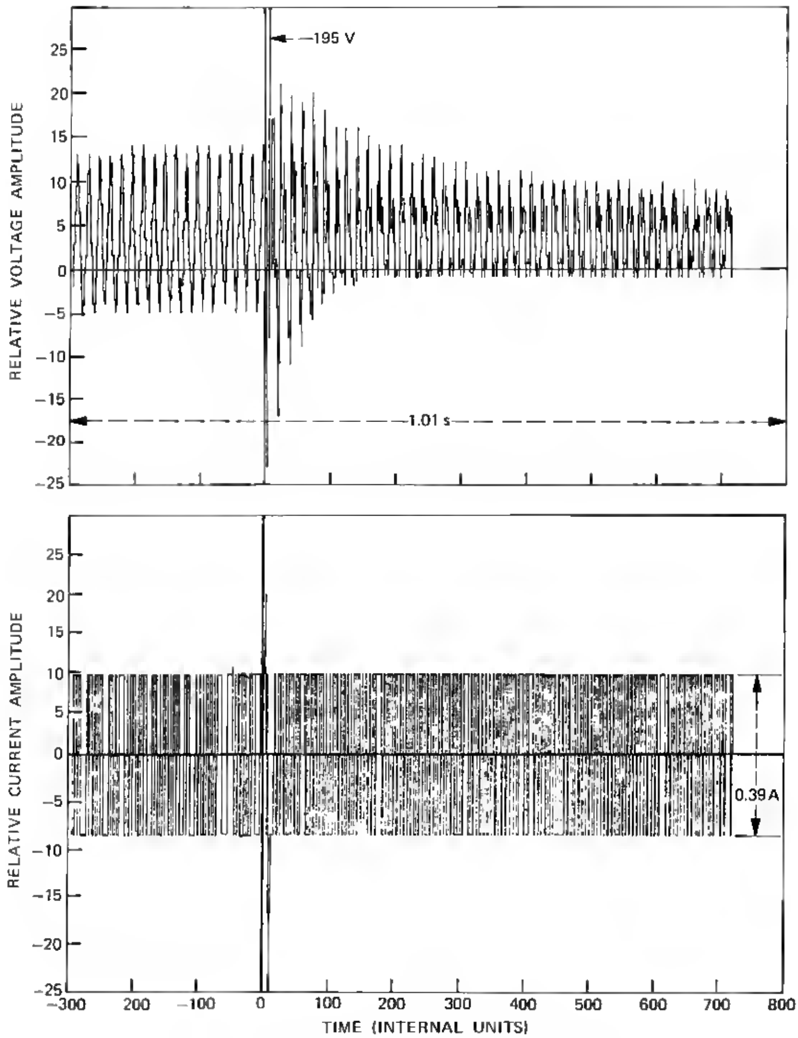

Fig. 42—Waveform recorded at rms sweep rate.

were observed. Other more complex lightning waveforms were obviously distortions of exponentials produced by breakdown of components within the loop plant or by reflections. This is in contrast to the results in Washington, Connecticut, which showed no waveforms well approximated by an exponential. The system acquired 2387 lightning associated pulses with 1309 identified as first strokes. The median peak lightning voltage was 367 V, while the system maximum of ±1000 V was exceeded on several occasions. The median peak lightning current was 0.59 A, and the system maximum of 25.0 A was attained once but not exceeded.

Both voltage and current peak magnitude distributions as well as the average number of events per thunderstorm day exceeding a given level were found to be less severe than comparable data from Washington, Connecticut. The larger lightning current magnitudes occurred on first strokes.

Rate of rise calculations were complicated by the presence of high amplitude narrow transients with computed rates of rise up to 788 V/μs superimposed on many lightning waveforms. When these impulses are removed, the rate of rise distribution is considerably less severe than that obtained in Washington, Connecticut, where such narrow spikes could not be processed.

The energy associated with a lightning event of a given amplitude was for most voltage waveforms and for all current waveforms bounded above by that of a 1000 μs decaying exponential waveform of the same peak magnitude. Both voltage and current energy showed a moderate positive correlation with peak magnitudes.

The median lightning voltage decay time based on voltage was about 0.54 ms with a maximum observation of 3.01 ms. The Washington voltage decay time distributions ranged beyond the Cleveland data in the upper tails. Although up to 13 strokes per lightning flash were recorded, the average was only 1.8 strokes per flash. The distribution of time between flashes was similar to that found in Washington.

Disturbances from an automatic oil switch in a nearby power system capacitor bank produced 5480 records with durations reaching 144 ms. These waveforms consisted of a succession of damped sinusoids with a median voltage just less than the lightning median, and a median current twice that of the lightning waveforms. The maximum current due to this source was 3.1 A, as opposed to the 25.0 A lightning maximum.

The rms detector was activated 27 times when induction from the power system exceeded 100 V rms for at least 0.25 second. The maximum current was about 0.2 A peak and the maximum voltage was 195 V peak.

XVI. ACKNOWLEDGMENTS

The development and installation of the transient monitoring system was made possible by the efforts of several individuals. Particular thanks are due to R. F. Youhas of Bell Laboratories who developed and interfaced the TMS subsystems, and to Norman Haskell, R. T. Banks, and C. Cannon of Southern Bell Telephone Company who coordinated acquisition, construction, and maintenance of the monitoring site.

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